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Numerical analysis study of the failure mechanism of transparent materials during low velocity impact used in protective systems

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ABSTRACT

The rapid advancement of computing power and recent advances in numerical techniques and material models have resulted in accurate simulation of ballistic impacts into multi-layer transparent armor configurations. Transparent and opaque materials are used in protective systems for enhancing survivability of ground vehicles, air vehicles, and personnel. Transparent materials are utilized for face shields, riot gear, and vehicle windows, in addition to other applications for sensor protection, including radomes and electromagnetic (EM) windows. For both transparent and opaque protective systems, low velocity impact damage can compromise structural integrity and increase the likelihood of further damage or penetration from a high velocity impact strike. Modeling and simulation of material impact by various threat types has proven to be a significant analysis tool in the identification of damage mechanisms and the failure process. The impact of laminate targets consisting of a series of glass layers adhered to each other by polyurethane and backed by a polymeric backing layer, was modeled and simulated. The failure mechanism of laminate targets was studied by ANSYS/AUTODYN [1] commercial software and the results were compared to available experimental data from various nondestructive techniques. Successful output of this modeling effort will provide useful information for the mitigation of damage propagation through targets used in protective systems and it will help to establish an economical damage acceptance criterion for any future material prior to its fielding.

INTRODUCTION

The U.S. Army has invested heavily in the development of next generation materials, including ceramics, for military systems [2]. Among the potential ceramic materials considered for armor — sapphire, edge-form-growth sapphire, magnesium aluminate spinel, aluminum oxynitride — one was selected for the current pursuit, glass. Individual transparent materials used in protective systems typically consist of glass or other transparent materials, polymeric and/or ceramics, which were stacked and adhered by polymer interlayers to form interlayers to form transparent laminate protective systems [3]. In particular, glass is an appealing transparent material due to its availability and low cost. The presence of potentially harmful internal defects in these individual materials (pores, inclusions, secondary phases, etc.) and interlayer defects in the laminates (disbands, delamination, etc.) can reduce material properties but may not be visually detectable if index-matched [3].

Current strike face glasses used in transparent laminate protective systems are limited in how thin they can be fabricated before encountering durability issues. Lower density novel glass components have been developed that can be fabricated more than ten times thinner while maintaining their durability. By reducing the thickness and lowering

the density of the strike face glass, the overall weight will also be reduced. Weight reduction is desirable for vehicle systems to increase maneuverability and transportability while reducing operational costs [4].

Nondestructive bulk characterization techniques can be utilized in the pre-impacted state to detect material inhomogeneities and improve quality control for transparent materials before they are utilized in the field. They can also be used post-impact to detect resulting damage and a comparison of baseline and damaged states can be established to help determine critical impact conditions [4].

The damage resulting from standard projectile impact on a brittle target has been studied extensively over the past decades and it corresponds to the three stages [5-9]:

1. Crushing occurs in the high pressure compressive zone in the region of contact, which is associated with the onset of micro-cracking, the formation of interconnected cracks and fragmentation (loss of ceramic continuity).
2. The dynamic erosion at the interface between the ceramic and the projectile proceeds by a process of high pressure grinding and the mixture of target and impactor particles is accelerated and ejected from the front surface of the target.
3. The size distribution of the ceramic fragments is determined by the network of radial, transverse and spall cracks spreading from the contact zone determines. The constraint of the target is expected to affect mostly these failure processes.

The propagation of cracks in brittle solids, such as ceramics, results in their failure. Various defects in the ceramics such as, holes, inclusions, microcracks and surface scratches facilitate the nucleation and propagation of cracks by Ashby et al.[10]. Ashby and Sammis [9] reported that “the difference between compressive and tensile fracture is that in tension a single crack grows unstably (once started, it accelerates across the sample to cause failure) while in compression a population of small cracks extends stably, each growing longer as the stress is raised, until they interact in some cooperative way to give final failure. Because of this, the strength of a brittle solid in compression is usually greater, by a factor of ten or more, than that in tension”.

Finite element modeling has progressed substantially in the ability to predict failure of materials under extreme dynamic loading conditions. One of the limitations of predictive models is lack of a complete dynamic materials properties database which is needed for materials models for each of the materials in the simulations. In order to compensate for parameters whose dynamic values were extrapolated from their static or quasi-static properties, baseline experiments are often used to recalibrate the models [11, 12]. However, the recalibration method of modeling lacks many of the physical properties and failure mechanisms associated with real-world materials. Therefore, recalibrated models often lack the ability to predict within statistical error future failures over any substantial ranges due to the existence of defects, and materials substitutions often lead to new calibration requirements. The desired approach is to validate a fully characterized materials database with one calibration model, and subsequently apply the model to modified designs. However, despite its apparent problems, recalibration of existing materials models has been proven to be an effective tool in the hands of the modeler by minimizing the number of simulation iterations, resulting in more successful predictions. Regardless of methodology, finite element tools can be applied effectively to reduce the variability between impact tests and can be used to validate designs with fewer experimental failures, when robust models are created [11]. The result of the on-going investments is a critical understanding of ceramics strengths and weaknesses for military platforms.

EXPERIMENTAL

The transparent materials chosen for this study were four 14-inch by 14-inch laminate panels designated as 740 and 741 series.. Each laminate consisted of a glass strike face, Glass A and Glass A' for 740 and 741 series, respectively, a central glass layer (Glass C), a polycarbonate backing and a polyurethane adhesive layer between the neighboring laminates. The total thickness of 740 and 741 series laminates was 23 mm and 17 mm respectively. The thickness and properties of strike face Glass A of laminate 740 were different than the corresponding ones of the face glass A' of 741-series. Both laminates were impacted by 4340 steel spheres of 19.05 mm and 5.56 mm diameter respectively. The laminates which were impacted by the 19.05 mm spheres were labeled as 740-1 and 741-1 respectively. The laminates which were impacted by the 5.56 mm sphere were labeled as 740-2 and 741-2 respectively.

Visual characterization, cross-polarization imaging, ultrasonic testing, x-ray digital radiography, and x-ray computed tomography (XCT) were used for the nondestructive characterization of the laminates. Details of the nondestructive techniques used can be found in reference [3].

MODELING

The ballistic behavior of all targets, which consisted of glass and polycarbonate backing, and were held together by polyurethane and impacted by steel spheres of 19 mm and 5.56 mm diameter, were simulated using the non-linear ANSYS/AUTODYN commercial package [1]. The geometry of the 2D and 3D axisymmetric modeled laminates was identical to the actual geometry of the laminates (Figure 1 and Figure 2). Smooth particle hydrodynamics (SPH) solver was used for the laminate and the impactor. The element size was 0.2 mm for 2D modeling and 0.5 mm for the 3D modeling. The polycarbonate was simply supported at the corners by applying zero velocity along the x-direction as a boundary condition. Results were obtained by simulating a projectile impacting the targets at constant velocity of 400 m/s and 30 m/s respectively. The material models used for all materials were obtained from the AUTODYN material library [1]. The polycarbonate (PC) was modeled using a shock equation of state (EOS), piecewise Johnson-Cook (JC) strength model, and a plastic strain failure criterion. The projectile steel was modeled using a shock EOS and a JC strength model. The glass was modeled using a polynomial EOS and Johnson-Holmquist (JH2) strength and failure models. The polyurethane was modeled using linear EOS, elastic strength model and principal stress tensile failure.

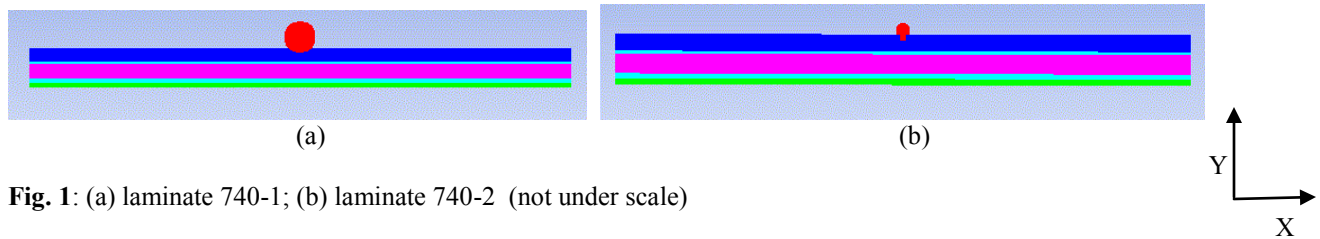


Fig. 1: (a) laminate 740-1; (b) laminate 740-2 (not under scale)

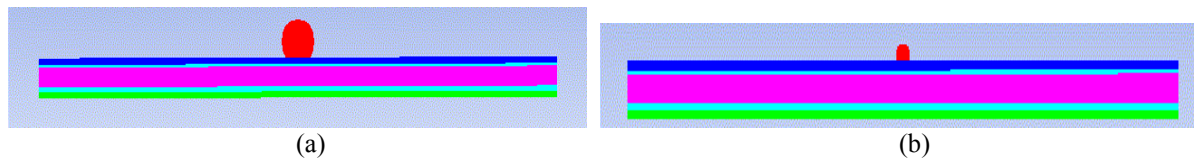


Fig. 2: (a) laminate 741-1; (b) laminate 741-2 (not under scale)

RESULTS

Figure 3 shows the XCT cross-section images of all four laminates prior and after the impact. Cone cracking appears in Glass C for 740-1 and 741-2 laminates. Simulations also showed similar cracking pattern for



Fig 3 XCT cross section images of all laminates prior and after the impact (-1 designates impact by a 19.05 mm steel sphere, and -2 designates impact by a 5.56 mm sphere)

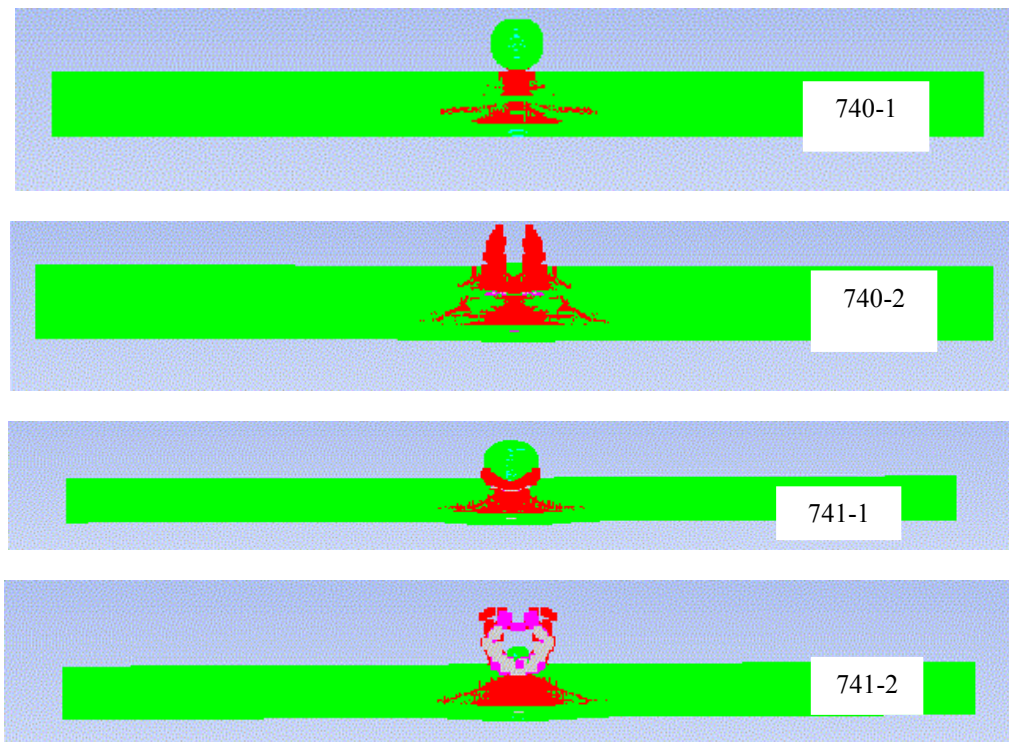


Fig. 4 2D simulated cross section images of all laminates after 50 μ s impact

the same laminates 740-1 and 741-2. Moreover, the characteristic comminuted zone below the center of impact and the tensile cracking of glass appears in all simulations. The simulation results agree with the experimentally

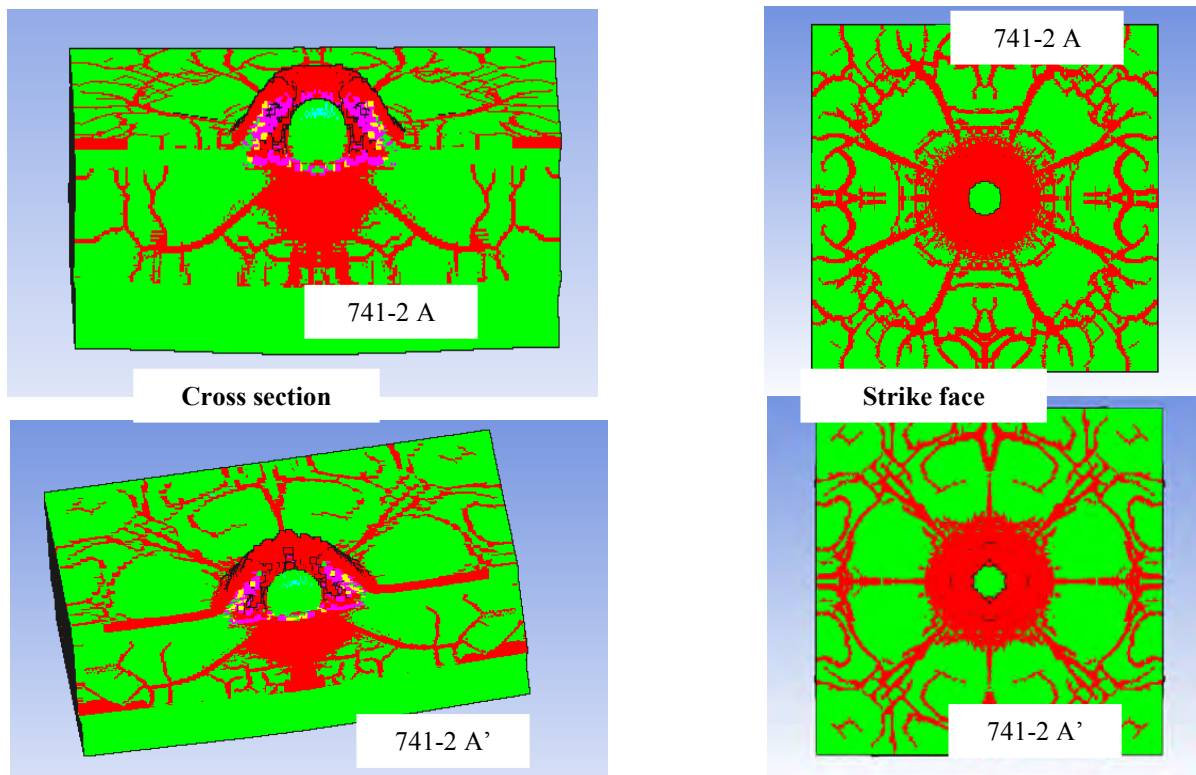


Fig. 5 Simulated damage for 741-2 geometry using Glass A and Glass A' as strike face after 30 μ s

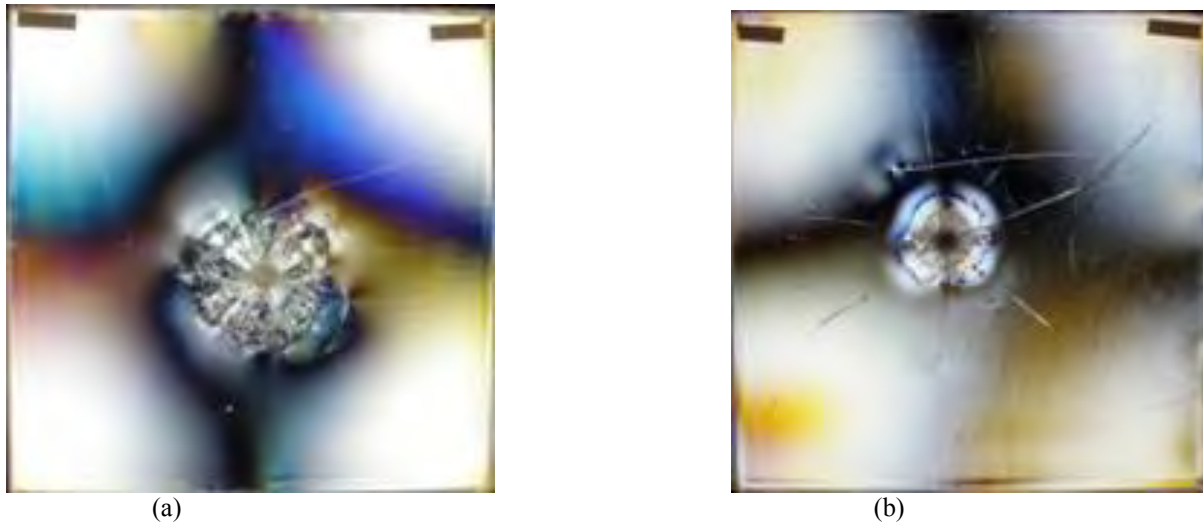


Fig. 6 Cross-polarized images of 740-2 (a) and 741-2 (b) laminate targets

observed data. The experimentally observed extension of the of the strike face damage into the central glass layers, was captured by all simulations. Careful examination of the cross-sections of the 2D simulations (Fig. 4) shows more cracking near the striking face of the 740-1 and 740-2 laminate targets than the cracking shown in 741-1 and 741-2 laminate targets. These simulation results agree well with the experimental results (Fig. 6). To further test the experimental observation that the 741-series transparent laminate system was the preferred choice due to the reduced average damage and less radial cracking that resulted in significant optical distortion [3], 3D impact simulations of 741-2 laminates were conducted. For this comparison, the Glass A' of the 741-2 target geometry was replaced by a similar thickness Glass A. After 30 μ s simulation, the cracking of the 741-2 target having Glass A as the striking face was more extensive than the cracking of 741-2 with Glass A' as the striking face. Moreover, the simulations showed higher density of tensile cracking at the periphery of the pulverized zone around the center of impact for the 741-2 (Glass A) case, in agreement with the experimental results shown in Fig. 6.

CONCLUSIONS

The failure mechanism of two different thickness laminate targets impacted at 30 m/s and 400 m/s by steel spheres was studied by 2D and 3D modeling and simulation. The results of the simulation compared well to the experimental data. The surface and interior failure of the laminate targets was observed experimentally by using a combination of various techniques such as visual characterization, cross-polarization image, ultrasonic testing, x-ray digital radiography, and x-ray computed tomography (XCT). The simulations replicated successfully the experimental surface and interior failure of the targets. Details of the failure of individual plies in the laminate target were observed and studied by simulation. It was shown that the damage of the surface is reflected in the central glass, an indication of the damage created by the propagating shock wave impact ahead of the penetrating projectile. In addition, the simulations replicated the bulging of the actual polycarbonate backing layer. The successful replication of the experimental data and the failure details of the laminate target suggest that modeling and simulation can be implemented as the initial decision making stage for examining current and future target architectures, thus decreasing the cost of the necessary experiments and NDE techniques.

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